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Soil Profile Water Content Determination: Sensor Accuracy, Axial Response, Calibration, Temperature Dependence, and Precision

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ABSTRACT

Although the neutron moisture meter (NMM) has served the need for accurate soil water content determinations well, increasing regulatory burdens, including the requirement that the NMM not be left unattended, limit the usefulness of the method. Newer methods, which respond to soil electromagnetic (EM) properties, typically allow data logging and unattended operation, but with uncertain precision, accuracy, and volume of sensitivity. In laboratory columns of three soils, we compared the Sentek EnviroSCAN and Diviner 2000 capacitance devices, the Delta-T PR1/6 Profiler capacitance probe, the Trime T3 tube-probe, all EM methods, with the NMM and conventional time domain reflectometry (TDR, also an EM method). All but conventional TDR can be used in access tubes. Measurements were made before, during, and after wetting to saturation in triplicate repacked columns of three soils ranging in total clay content from 17 to 48%. Each column was weighed continuously, and thermocouple determinations of temperature were made every 30 min throughout. All of the devices were sensitive to temperature except for the NMM, with conventional TDR being the least sensitive of the EM devices (sensitivity $<|0.0006|$ m^3 m^{-3} C^{-1}). The Trime T3 and Delta-T PR1/6 devices were so sensitive to temperature (0.015 and 0.009 m^3 m^{-3} °C^{-1}, respectively, in saturated soil using soil-specific calibration) as to be inappropriate for routine field determinations of soil profile water content. Temperature sensitivity was up to 12 times larger in saturated soils compared with values in air-dry soils, corresponding to the much larger bulk electrical conductivities of these soils when saturated. All devices exhibited estimation precision better than 0.01 m^3 m^{-3} under isothermal conditions. However, under nonisothermal conditions, estimation precision for the EM sensors worsened as the number of measurements (and time involved in taking readings) increased, and as the soils became wetter, resulting in precision values $>$0.01 m^3 m^{-3} for the Trime and Delta-T devices. Accuracy of the devices was judged by the root mean squared difference (RMSD) between column mean water contents determined by mass balance and those determined by the devices using factory calibrations. Smaller values of the RMSD metric indicated more accurate factory calibration. The Delta-T system was least accurate, with an RMSD of 1.299 m^3 m^{-3} at saturation. At saturation, the Diviner, EnviroSCAN, NMM, and Trime devices all exhibited RMSD values $>$0.05 m^3 m^{-3}, while TDR exhibited RMSD $<$0.03 m^3 m^{-3}. Soil-specific calibrations determined in this study resulted in RMSE of regression values (an indicator of calibration accuracy) ranging from 0.010 to 0.058 m^3 m^{-3}. All of the devices would require separate calibrations for different soil horizons. Of the EM devices, only the Delta-T PR1/6 exhibited axial sensitivity appreciably larger than the axial height of the sensor, indicating small measurement volumes generally, and suggesting that these systems may be susceptible to small-scale variations in soil water content (at scales smaller than the representative elemental volume for water content) and to soil disturbance close to the access tube caused during installation.

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Accurate soil water content estimations are required for determinations of crop water use, water use efficiency, irrigation efficiency, and in soil hydrology. For nearly 50 yr, the NMM has served this need well, but increasing regulatory burdens, including the requirement that the NMM not be left unattended, limit the usefulness of the method, particularly for unattended, automated data acquisition. In many field experiments, these limitations prevent the method from being useful for capturing the depth of water added to the soil via irrigation or precipitation without confounding effects of crop water use, deep percolation, and/or evaporation from the soil surface that occur between measurements. Since 1980, several methods have been brought to the scientific market that rely on responses to soil EM properties as a surrogate for soil water content (Topp et al., 1980; Dean et al., 1987; Paltineanu and Starr, 1997). These EM methods typically allow data logging and unattended operation, but with uncertain precision and accuracy (Baumhardt et al., 2000; Evett and Steiner, 1995; Kelleners et al., 2004a, 2004b), probably related to small measurement volumes and sensitivity to bulk electrical conductivity and temperature.

All of the EM methods generate an electrical signal and measure some property (typically a frequency or travel time) of the response of this signal to changes in the apparent permittivity of the soil, ε_a. For a signal at a single angular frequency, ω, the effect of direct current electrical conductivity, σ_{dc}, on the apparent permittivity can be represented by (Robinson et al., 2003)

$$\varepsilon_a = \frac{\mu\varepsilon'}{2}\left(1+\left\{1+\left[\left(\varepsilon''_{relax}+\frac{\sigma_{dc}}{\omega\varepsilon_o}\right)\Big/\varepsilon'\right]^2\right\}^{0.5}\right) \quad [1]$$

where ε' is the real component of the complex dielectric permittivity, ε''_{relax} is the increase in permittivity due to relaxation losses, and ε_o is the permittivity of free space (8.854×10^{-12} F m^{-1}). The value of ε' is largely dependent on the permittivity of the free water in soil, but the value of ε_a is dependent also on the measurement frequency, the value of σ_{dc}, and relaxation effects. Thus, temperature sensitivity of EM methods may be due to, among other causes, the temperature sensitivity of soil bulk electrical conductivity (σ_a, S m^{-1}), the negative temperature dependence of the permittivity of free water (-0.41 to -0.33 °C^{-1} from 0 to 40°C), and the effect of σ_a changes on the effective measurement frequency (Evett et al., 2005). The apparent permittivity may also increase with the release of bound water from

Abbreviations: EM, electromagnetic; NMM, neutron moisture meter; RMSD, root mean squared difference; RMSE, root mean squared error; TDR, time domain reflectometry.

soil particle surfaces as temperature increases (Wraith and Or, 1999).

It is well known that the value of ε_a increases with soil σ_a (Wyseure et al., 1997; Robinson et al., 2003), particularly for σ_a >0.2 S m^{-1}. Also, the value of σ_a increases with soil water content and temperature (Rhoades et al., 1976; Mmolawa and Or, 2000). However, due to the complex interactions of factors affecting permittivity, the value of ε_a may increase or decrease with temperature, depending on the soil texture and water content (Campbell, 1990; Pepin et al., 1995; Persson and Berndtsson, 1998; Wraith and Or, 1999), with nonsaline sandy soils more often displaying a negative temperature dependence of ε_a, as might be expected since such soils do not display increases in σ_a with increasing water content as do some nonsaline clayey soils. In the frequency range in which most capacitance soil water sensors operate (100s of MHz), the value of permittivity is frequency dependent and increases as measurement frequency decreases (Campbell, 1990). The operating principle of capacitance sensors is that the resonant frequency decreases as water content (permittivity) increases. Thus, there is likely a confounding effect of the frequency dependence of permittivity; and that effect is probably strengthened in soils with appreciable σ_a. In sum, there may be a nonunique relationship between water content and ε_a for capacitance sensors in warmer, wetter soils with larger σ_a.

Assuming that relaxation effects were negligible, Evett et al. (2005) determined a water content (θ_v, m^3 m^{-3}) calibration equation for conventional TDR in terms of σ_a, and the travel time (t_t, s) and effective frequency (f_{vi}, MHz) of the TDR pulse in a probe of length L (m):

$$\theta_v = -0.182 + 0.1271[c_o t_t/(2L)] - 0.004933[\sigma_a/(2\pi f_{vi}\varepsilon_o)]^{0.5} \quad [2]$$

While possibly not applicable in sandy soils, Eq. [2] was accurate to 0.01 m^3 m^{-3}, and it reduced temperature dependency of water contents estimated in the three soils studied here to <0.0006 m^3 m^{-3} °C^{-1}, employing only information available from the TDR waveform.

The apparent temperature sensitivity in terms of the water contents estimated using EM methods is affected by the shape of the calibration curve and the value of multiplicative coefficients in the calibration equations for each method. For a given sensitivity of the response variable (e.g., frequency or travel time), the sensitivity of estimated water content increases as the slope of the calibration equation increases. For curvilinear calibrations, this may compound the effect of temperature sensitivities at the wet end, at which slopes are typically larger.

Our objectives were twofold: (i) to compare, in three different soil materials, the accuracy, precision, temperature sensitivity, and axial sensitivity of several commercially available devices that could be used in access tubes to estimate soil water content in the root zone and below and (ii) to calibrate these devices in the three soils and compare these with factory calibrations. Comparisons of water content reported by each device were made vs. soil water content determined by mass balance in soil columns and by TDR using the Eq. [2] calibration.

Accuracy, Bias, and Precision

Accuracy, bias, and precision are key concepts in sensor evaluation and description. A more accurate sensor (or method) is one whose reading is closer to the true value of the property being sensed. Precision is related to the scatter of repeated readings around the mean sensor reading. A more precise sensor exhibits less scatter. It is important to note that a precise reading may be quite inaccurate, that is, it may be biased from the true mean. Thus, accuracy is affected both by sensor bias and precision. Calibration is the accepted method of removing or reducing sensor bias. Thus, any inaccuracy not removed by calibration may be considered to be related to sensor precision. Even if not biased, an individual reading from a less precise sensor is less likely to be close to the true mean. Moreover, the operational meaning of these terms is determined by the method by which they are evaluated and the context in which they are used. A common statistic used to evaluate the accuracy of a sensor is the RMSD between the sensor reading and the true value of the property. The true property value is, of course, determined by another method that will itself involve some error. It is common to determine the true value by a method that is known to be, or can be shown to be, sufficiently accurate so that whatever error is inserted into the measurement system by this method is smaller than some predetermined criterion. In soil water work, the standard method of determining the true value is mass balance; and the errors involved are those inherent in the mass determination; and if volumetric water content is desired, the error in volume determination. An example of the use of the RMSD would be when comparing water contents, estimated using the sensor with preset or "factory" calibration, with water contents determined by mass balance. In calibration work, a common statistic of accuracy is the root mean squared error (RMSE) of the calibration equation (Kempthorne and Allmaras, 1986), which is typically determined by linear or nonlinear regression of the sensor output versus the water content determined by mass balance. Discussion of which of these should be the independent variable is an important topic in statistics that has practical consequences for calibration of soil water sensors (Greacen, 1981) that will not be discussed here. Both the RMSD and the RMSE are used here, each in the appropriate context.

Precision may be evaluated by calculating the SD of water content estimations from repeated measurements with the sensor in some standard environment for which no variation of temperature or water content or other possible covariable is allowed. This definition of precision is of somewhat limited usefulness in that sensors are not typically used in such environments. Another method for evaluating precision is to make repeated measurements in a uniform medium, but inserting and removing the sensor at each measurement. If the insertion is into a number of access tubes in a field of uniform soil, then the value of precision so determined includes any variability due to access tube installation and contact with the soil (a real and important part of the sensing system), soil variability on the spatial scale at which the sensor operates (making the volume sensed an important sensor property), and variability in any covariates (e.g., temperature) that may interfere with the readings during the time it takes to make the repeated readings (making environmental sensor interferences important sensor properties). Because a user does not have perfect control over sensor or access tube installation, and has no control over the sensor's volume of measurement or environmental variables that may interfere, such as temperature, it makes sense to evaluate sensor precision under these real conditions of operation. In our study, we evaluated precision in a more perfect environment. Access tube–soil contact and soil uniformity at the small scale were made as near perfect as possible by packing crushed and sieved soil around the access tubes. Sensor precision was evaluated at the air-dry soil initial condition and at the completely saturated end point, both conditions under which soil water content could not vary appreciably. Sensors were not moved during the evaluation of precision. However, because soil temperature is known to interfere with EM sensors, we did allow soil temperature to vary. We evaluated precision using both short-term series of measurements, to minimize soil temperature variation and to approach the first (ideal) definition of precision given above, and long-term measurement series, during which temperature varied considerably so that precision values so determined included the variation due to any temperature effect on the sensor reading. We feel that this is a reasonable evaluation of precision because none of the sensors studied allowed for sensing of soil temperature, none of the sensor calibrations included temperature or a temperature-related covariate such as bulk electrical conductivity (except for the TDR system), and so none facilitated correction for temperature effects by a user.

METHODS AND MATERIALS

Three soils were acquired in fall 2000 at Bushland, TX, air-dried, crushed and sieved to ≤2-mm diameter (USDA-ARS Conservation & Production Research Laboratory, 35° 11′ N lat, 102° 06′ W long, 1170 m elev. above MSL). The soils were (i) a silty clay loam (30% clay, 53% silt), hereinafter referred to as Soil A; (ii) a clay (48% clay, 39% silt), Soil B; and (iii) a clay loam (35% clay, 40% silt) containing 50% $CaCO_3$ (17% total clay), Soil C. Soils A, B, and C were derived, respectively, from the A, Bt, and Btk horizons of a Pullman soil, which is a fine, mixed, superactive, thermic Torrertic Paleustoll with mixed clay mineralogy including large proportions of illite and montmorillonite (smectite). The difference in total clay content from 17% (of total mass, including the $CaCO_3$) to 30 to 48% between Soils C, A, and B, respectively, should illuminate any texture dependence of the devices. The 50% $CaCO_3$ content of soil C should illuminate effects of the carbonate content of caliche horizons, which are $CaCO_3$–rich horizons common in soils of the Great Plains and further west in the United States. These soils exhibit σ_a values that increase with both water content and clay content (Table 1), although the dependence of σ_a on water content is much less for the smaller-clay-content C soil than for the other two. Also, the temperature dependence of σ_a in the C soil is approximately one-half of that in Soils A and B. These same soils were used in the TDR calibration resulting in Eq. [2].

Each soil was packed uniformly into three replicate plastic columns. Soil in each column was 75 cm deep and 55 cm in diameter, and rested on a 5-cm-deep bed of fine pure silica sand in which was embedded a ceramic filter tube specified at 100-kPa air-entry potential (Fig. 1). Soil was packed in 5-cm layers around access tubes, which were held in place with a jig so that tube positions would be identical in each column. Distances between access tubes and between access tubes and column walls were great enough to be outside the radial distance within which 95% of the measurement influence can be found for the EM devices tested. For the conventional TDR systems, horizontal, trifilar TDR probes (20-cm length, Dynamax, Inc., Houston, model TR-100) were installed at depths of 2, 5, 15, 25, 35, 45, 55, and 65 cm in each column to determine soil water content (θ_v, m^3 m^{-3}) and bulk electrical conductivity (σ_a, S m^{-1}).[1] Type T thermocouples were installed at the same depths to determine soil temperature (T, °C). Three samples for initial gravimetric water content were obtained every two layers during packing. Column sides were covered with reflective aluminum foil to minimize daily heating and cooling on the sides. Column soil surfaces were left exposed to solar radiation and air temperature variations in the greenhouse that housed the experiment. The greenhouse was not cooled and was only heated sufficiently in winter to prevent freezing, the intention being to provide a wide variation in daily and seasonal temperature in the soils. Before wetting, the soil columns were flushed with CO_2 gas fed into the bed of sand at their bottoms to displace air in the pore space. The columns were then wetted from the bottom, displacing the CO_2. Any CO_2 not displaced dissolved in the water, resulting in completely saturated soil columns. Soil surface height was measured periodically as the soils wetted to adjust soil volume for swelling.

Column mass was determined every 6 s using a data logger (Campbell Scientific, Inc., Logan, UT, model CR7) connected to the paralleled output of the four load cells in each scale (Weigh-Tronix, Inc., Fairmount, MN, model DS3040-10K), using a six-wire bridge configuration to minimize temperature-induced errors. Mean values were output every 5 min. Calibration with test masses traceable to NIST resulted in RMSE values of linear regression ≤50 g for all scales. Initial volumetric water content of each column was computed from the mass of soil added, the volume of the column, and the water contained in the soil as determined from the gravimetric samples.

Estimates of θ_v and σ_a, using the 72 20-cm trifilar TDR probes, were made every 30 min using the TACQ program (Evett, 2000a, 2000b; Evett et al., 2005) controlling a conventional TDR system that included an embedded computer (IBM PC/AT compatible), cable tester (Tektronix Inc. Redmond, OR, model 1502C), and five coaxial multiplexers (Evett, 1998). Water contents were calculated both using Eq. [2] and the calibration of Topp et al. (1980). Thermocouples were sensed every 30 min using the CR7 data logger to determine T.

Three capacitance type soil water sensing systems were used (Delta-T Devices Ltd., Cambridge, UK, model PR1/6 Profile

[1] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

Table 1. Physical properties of the three soils.

Soil	Clay†	Silt	$CaCO_3$	σ_a,‡ Air-dry	σ_a,‡ Saturated	Temperature dependency of σ_a Air-dry	Temperature dependency of σ_a Saturated	Field bulk density
	% mass			dS m^{-1}		dS m^{-1} °C^{-1}		Mg m^{-3}
A	30	53	0.5	0.038	1.360	-9.47×10^{-5}	0.0336	1.42
B	48	39	3.5	0.039	1.471	-1.15×10^{-4}	0.0363	1.45
C	17.5	20	50	0.033	0.754	-8.57×10^{-5}	0.0163	1.41

† Percentage of total mass before carbonate removal.
‡ Bulk electrical conductivity at 25°C calculated from equations in Table 5 of Evett et al. (2005).

Probe; Sentek Environmental Technologies, Kent Town, South Australia, models EnviroSCAN and Diviner 2000).

The EnviroSCAN system features a string of sensors placed every 10 cm on a plastic backbone through which a communications cable runs to the sensor-string head. Sensors were centered at 5-, 15-, 25-, 35-, 45-, 55-, and 65-cm depths. One string of sensors was placed in one column of each soil and logged continuously every 30 min. The Diviner 2000 consists of a single sensor, similar to that used in the EnviroSCAN, fitted to a square rod that allows the sensor to be lowered to the 1.6-m depth in an access tube. The same size PVC plastic access tube is used for both Sentek systems (5.1-cm i.d., 5.6-cm o.d.). We made readings periodically in two columns of each soil with the Diviner 2000 at the same depths as for the EnviroSCAN. Output from the Sentek systems is a count proportional to the sensor circuit (resonant) frequency. This count is scaled to a value between zero and unity called the scaled frequency, S_F

$$S_F = (C_A - C_S)/(C_A - C_W) \qquad [3]$$

where C_A is the count with the sensor in the access tube, which is itself surrounded by air; C_S is the count with the access tube surrounded by the soil; and C_W is the count with the access tube surrounded by nonsaline water. Actual sensor frequencies are 4096 times the recorded counts (Sentek, 1994), and

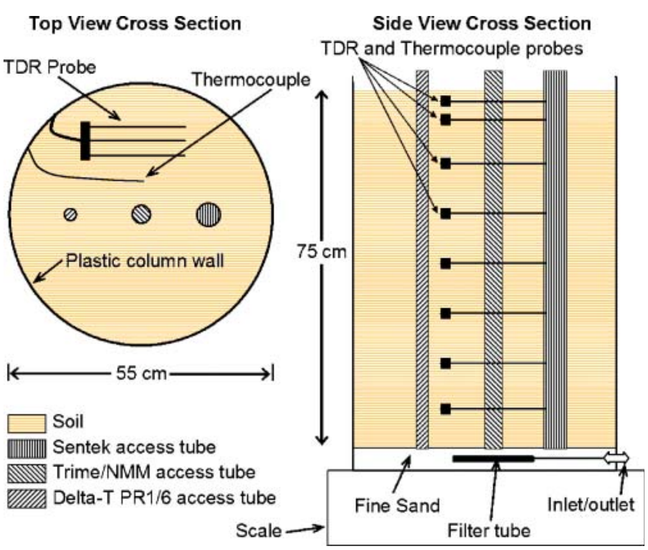

Fig. 1. Top and side view cross sections of a soil column showing the placement of access tubes, TDR probes, and thermocouples. Column sides were covered with aluminum foil. For axial sensitivity tests, each sensor was centered above its access tube and at a height (usually 30 cm above the soil surface) such that the soil (either dry or saturated) did not influence the sensor reading. Then the sensor was lowered in 2-cm increments, with a reading taken at each increment, until it passed through the access tube and reached a position below the soil surface that was lower than the depth at which further lowering did not influence the sensor reading (usually 30 cm below the soil surface).

frequencies range from approximately 100 MHz for C_W to approximately 150 MHz for C_A. However, in the range of permittivities relevant to soil water systems, EnviroSCAN S_F values range from ~0.35 in air-dry soil to ~0.95 in saturated soil; corresponding sensor resonant frequencies vary from ~133 to ~105 MHz. Diviner 2000 frequencies range from ~240 to ~330 MHz, corresponding to C_W and C_A counts, respectively; the range in soils is from ~250 MHz in saturated soil to ~287 MHz in air-dry soil. Accuracy was not specified in units of soil water content.

The PR1/6 probe has six capacitance sensor element pairs on fixed spacing on a monolithic round plastic rod. The sensor centers of measurement are at depths of 10, 20, 30, 40, 60, and 100 cm. In use, the rod is lowered into an epoxy-fiberglass access tube (26-mm i.d., 28-mm o.d.). In our study, the rod was positioned so as to obtain readings at 5, 15, 25, 35, 45, 55, and 65 cm. Because the cylindrical plates that form the capacitance element in this sensor have a gap on one side, two readings were made at each depth, with the probe rotated 90° around its axis after the first reading to ensure full coverage. The PR1/6 operates at approximately 100 MHz, and its output is a voltage (V) ranging from zero to ~0.4 V and exhibiting a curvilinear relationship with $\varepsilon^{0.5}$ (Delta-T Devices Ltd., 2001). Accuracy is stated as ± 0.05 m^3 m^{-3} (0–0.6 m^3 m^{-3}, 0–40°C) using the factory calibration and ± 0.03 m^3 m^{-3} using soil-specific calibration, with errors of less than -0.0001 m^3 m^{-3} per mS m^{-1} in soils with σ_a of up to 8 dS m^{-1}.

The NMM (Campbell Pacific Nuclear International, Inc., model 503DR1.5) was used with a depth control stand (Evett et al., 2003) for measurements centered at the 10-cm depth and in 20-cm increments below that. Factory calibrations for the NMM are known to be inaccurate in many soils (Hignett and Evett, 2002). Because the soil columns were too small to entirely contain the neutron flux in the air-dry condition, the NMM was field calibrated. Using methods described by Hignett and Evett (2002), the accuracy (field calibrated) should be at least 0.01 m^3 m^{-3} and insensitive to σ_a.

Finally, we used the Trime T3 tube probe, which is a cylindrical probe with two waveguides oriented vertically on opposite sides of a cylindrical plastic body (IMKO Micromodultechnik, GmbH, Ettlingen, Germany, model TRIME-T3 Tube Access Probe). The measurement length of the T3 probe is 17.5 cm. The probe is suspended from a cable and lowered to any desired depth in the polycarbonate plastic access tube (41-mm i.d., 44-mm o.d.). Using a depth control stand, we made measurements at 17.5-cm depth intervals with the topmost measurement centered at 8.75 cm below the soil surface. Daily measurements were made. A measurement was also made with the probe resting against the bottom of the access tube. The T3 probe was matched with the Trime-FM field measuring device, which sends a fast rise time pulse through a coaxial cable to the probe and outputs a "pseudo" transit time that is related to water content. Transit times are determined using a voltage comparator that is set in sequence to a series of voltage levels, at each of which the reflected signal is timed until its voltage equals or exceeds that of the comparator.

Thus, a series of transit time measurements are acquired. The complete waveform is not acquired. Thus, unlike conventional TDR systems, the Trime-FM does not acquire or output a waveform, nor does it perform an internal waveform analysis by tangent line fitting. The voltage comparator is located in the Trime-FM, so transit times must include any variation in pulse travel time along the 3-m coaxial cable. Resolution is stated as 3 ps, and accuracy as ± 0.03 m^3 m^{-3} (0–0.6 m^3 m^{-3}) for $\sigma_a \leq 1$ dS m^{-1} (IMKO, 2000).

For each EM sensor except conventional TDR, nonlinear regressions of water content as determined by the calibrated TDR system versus sensor output were done using the SigmaPlot software (Systat Software Inc., SigmaPlot version 9.0). For the three capacitance systems, readings were taken at the same depths as with the TDR system, so water contents and sensor outputs from equivalent depths were paired directly in the data sets. For the Trime system, the TDR-determined water contents were interpolated to find mean water contents for depth intervals equivalent to those read by the Trime tube probe. Because on the dry end the volume of measurement of the NMM exceeded the volume of the soil columns, calibration of the NMM was not attempted using data from the soil columns. Instead, a field calibration was done using the methods of Evett and Steiner (1995) in the Pullman soil at Bushland in the horizons from which Soils A, B, and C were derived.

Axial sensitivity was determined by lowering each sensor in 2-cm increments from a height well above the air-dry soil surface to a depth well below the soil surface (high enough above and deep enough below the soil surface, respectively, so that readings did not change with vertical position). Data from three replicates were fitted using SigmaPlot to a four-parameter sigmoidal curve

$$\theta_v = y_0 + a/\{1 + \exp[-(z - z_0)/b]\} \quad [4]$$

where y_0, a, z_0, and b were fitted parameters and z was the height of the sensor center relative to the soil surface. The value of y_0 represented the minimum reading, which was obtained when the sensor was well above the soil surface, and the value of $y_0 + a$ represented the maximum reading obtained with the sensor well below the soil surface. A 90% axial response height was determined as the difference between the z value at which θ_v was 5% less than $y_0 + a$ and the z value at which θ_v was 5% more than a.

To test for temperature sensitivity, periodic (15–30 min) measurements were made over at least 2 d in the air-dry soil columns with a sensor of each device centered at the 25-cm depth for comparison with data of temperatures at that depth. Tests of sensitivity to temperature and to the soil–air interface were repeated when the soils reached saturation. The soil-specific calibrations determined during this study were used to calculate water contents from sensor readings taken during the temperature sensitivity measurements.

Precision can be assessed through repeated measurements with time (usually made with the sensor in one place and condition), or through repeated measurements across space, as in the field. In the latter case, variability in time is typically confounded with variability in space. Another variability assessment is one done with multiple sensors of the same type each placed in an identical environment, in which case the intersensor variability is assessed. We made repeated measurements with the subject sensor in one place in a soil column to measure variability with time. The SD was assessed by including four consecutive measurements in the calculation, then the next four, etc. until all the data had been used to calculate SD values, resulting in data on the running value of SD for the time period involved. The SD was alternatively calculated by first using four measurements (made at 15- or 30-min intervals depending on the sensor involved), then 8, then 12, etc. until 4 d of measurements were included in the calculation, resulting in SD values for a range of periods of measurement. Sensors with automatic data logging were read for longer periods; those that required manual operation were read for up to 1 d. The second SD calculation was done to see if SD was stable, decreased, or increased as the number of samples included in the calculation increased and as temperature fluctuations increased during the longer periods.

RESULTS

After packing, the soil columns had mean initial water contents of 0.051, 0.056, and 0.041 m^3 m^{-3} for Soils A, B, and C, respectively, and mean bulk densities of 1.48, 1.47, and 1.40 Mg m^{-3}, respectively.

Reported Water Contents in Air-Dry and Saturated Soils

The factory calibration for each system was used to calculate reported water contents from raw sensor outputs. In air-dry soils water content values from the Trime tube probe ranged from 0.037 to 0.059 m^3 m^{-3} larger than water content calculated from mass balance (Table 2). The Diviner reported mean water contents ranging from 0.021 to 0.040 m^3 m^{-3} larger than actual values. The EnviroSCAN was more accurate, reporting mean water contents ranging from 0.003 to 0.024 m^3 m^{-3} larger than actual. The Delta-T probe was most inaccurate, reporting mean water contents ranging from 0.085 to 0.096 m^3 m^{-3} larger than actual. The conventional TDR and NMM were most accurate, giving readings within 0.015 m^3 m^{-3} of those determined by mass balance. The good accuracy of the NMM in dry soil using the factory calibration was essentially an accident since (i) the soil columns were not large enough to represent an equivalent infinite volume of air-dry soil and (ii) other access tubes were close enough to represent voids within the measurement volume of the NMM. For these reasons, when field calibrations were used, water content was underestimated by 0.066 m^3 m^{-3} on average using the NMM.

In saturated soils and using factory calibration, only conventional TDR (using the Topp et al., 1980 calibra-

Table 2. Air-dry and saturated column mean volumetric water contents (θ_v, m^3 m^{-3}) by mass balance, and device errors (m^3 m^{-3}) calculated using factory calibrations.

Soil	Mass balance θ_v	Error–Difference from VWC by mass balance					
		Delta-T PR1/6	Diviner 2000	Enviro-SCAN	Trime T3	NMM	TDR
			Air-dry				
	m^3 m^{-3}						
A	0.051	0.093	0.021	0.003	0.037	−0.004	−0.015
B	0.056	0.096	0.024	0.024	0.054	−0.004	−0.009
C	0.041	0.085	0.040	0.019	0.059	−0.012	−0.001
RMSD†		0.091	0.030	0.018	0.051	0.007	0.010
			Saturated				
A	0.433	1.339	0.084	−0.037	0.064	−0.093	0.002
B	0.474	1.312	0.001	−0.062	0.088	−0.117	0.004
C	0.481	1.244	−0.037	−0.104	0.055	−0.106	−0.042
RMSD		1.299	0.053	0.073	0.070	0.106	0.024

† Root mean squared difference.

tion) was reasonably accurate, reporting water contents within 0.024 $m^3 m^{-3}$ of mass balance on average. For the other sensors, accuracy decreased in the order: Diviner 2000, Trime T3, EnviroSCAN, NMM, and Delta-T PR1/6 (Table 2). The Delta-T reported unrealistic water contents ranging from 1.24 to 1.34 $m^3 m^{-3}$. The variation of the degree and sign of errors among soils indicated that soil-specific calibrations were required for all of these sensors, with the possible exception of conventional TDR (depending on the need for accuracy). In fact, Evett et al. (2005) showed that including bulk electrical conductivity and effective frequency (both of which can be determined from TDR waveforms) in the calibration model can produce a common calibration for these three soils, with an accuracy of 0.01 $m^3 m^{-3}$. The inaccurate estimations from the NMM using the factory calibration support the statement that factory calibrations for the NMM are seldom useful (Hignett and Evett, 2002). The NMM was accurate to within 0.016 $m^3 m^{-3}$ in all three saturated soils (data not shown) when using field calibrations for the soil horizons represented by Soils A, B, and C, including the separate calibration for the 10-cm depth (e.g., Evett and Steiner, 1995).

Sensitivity to the Soil–Air Interface for Air-Dry Soil

The NMM had a 90% response window of 28 cm, as expected, more than twice its detector tube length of 13.2 cm (Table 3). The response window was centered at 6.0 cm below the soil surface; this result was not unexpected because the radioactive source is located just below the detector tube. The Delta-T probe 90% response window was centered at −0.4 cm, just below the soil surface, and had a height of 8.0 cm, almost twice the sensor height (Fig. 2). However, the 2-cm depth increment used between measurements may not have been small enough to obtain good precision with this probe, which had the smallest height. The Diviner had a 90% response window of 6.0 cm, almost the same as the 6.2-cm sensor height. The sensor response was centered at 1.5 cm below the soil surface. The EnviroSCAN sensor is very similar to that of the Diviner, but is difficult to move within the access tube. For these reasons, we did not test soil–air interface sensitivity of the EnviroSCAN sensor in dry soil. The Trime probe, with a sensor height of 17.5 cm, achieved 90% response for an 18-cm-high window. Sensor response was centered at 1.75 cm above the soil surface. Of the EM methods, only the Delta-T

Table 3. Axial response to the soil–air interface.

Instrument	Sensor height/ diameter	Height of 90% response window		Ratio of response to sensor heights	
		Dry	Wet	Dry	Wet
	cm				
Delta-T PR1/6	4.8/2.5	7.4	5.6	1.54	1.16
Sentek Diviner	6.3/4.7	6.2	3.1	0.99	0.50
Sentek EnviroSCAN	6.2/5.05	NA†	3.9	NA	0.63
Neutron probe	13.2/3.8	27.7	15.6	2.10	1.18
Trime T3	17.5/4.2	16.9	18.3	0.97	1.04

† NA means not available.

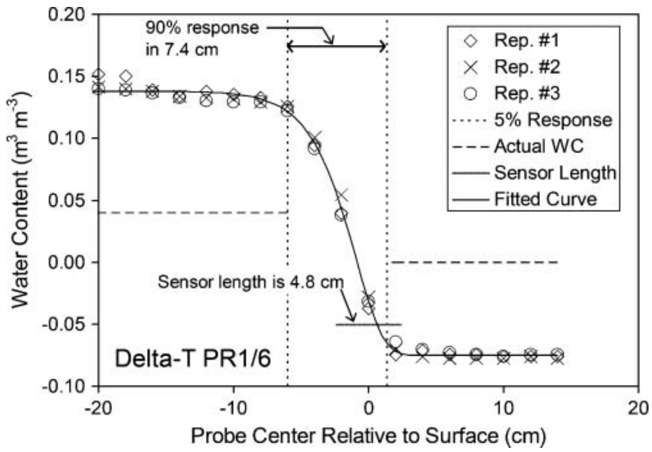

Fig. 2. Example of data for axial sensitivity tests showing axial response of the Delta-T PR1/6 instrument in air-dry soil. Positive *x* axis numbers are for sensor heights above the soil surface.

appeared to be sensitive to changes in the sensed medium above and below the active electrodes of the sensor.

Sensitivity to the Soil-Air Interface for Saturated Soil

When the soil was saturated, the height of the 90% response window was smaller (compared with the air-dry case) for every sensor except the Trime (Table 3), which acts more as a transmission line rather than as an antenna, and which responds to the travel of a pulse along the complete length of this line. The capacitance sensors act as weak antennas whose field collapses as the permittivity of the surrounding medium (the soil) increases. For the Diviner, EnviroSCAN, and Delta-T sensors, the response heights decreased to 0.50, 0.63, and 1.16 of the sensor height, respectively, in saturated soil. The ratios of response to sensor heights vary in inverse relationship to the measurement frequency of these three sensors, indicating that as measurement frequency increases, the sensed volume may decrease. Data of Paltineanu and Starr (1997) show that 90% of the EnviroSCAN response volume is within 3 cm radially of the access tube wall. If this is true for the Diviner 2000, as seems probable, then these sensors exhibit measurement volumes <400 cm^3 compared with the >14 000 cm^3 volume sensed by the neutron probe in saturated clay soil (Eq. [3.1.3–49] of Hignett and Evett (2002) with $\theta_v = 0.50$ $m^3 m^{-3}$ and a 4.45-cm o.d. access tube). All of the capacitance sensors will have a limited field of influence beyond the sensor body in saturated soils. Only the NMM and PR1/6 demonstrated 90% response windows appreciably larger than their sensor heights in saturated soils.

In both air-dry and saturated soil, the Trime was the only sensor that had an asymmetrical response (Fig. 3), such that its response was weighted toward one end of the probe. This contrasts with the linear response that is observed when a TDR probe is inserted into dry or saturated soil, an indication that, while acting like a transmission line device, the Trime is not acting like a conventional TDR system.

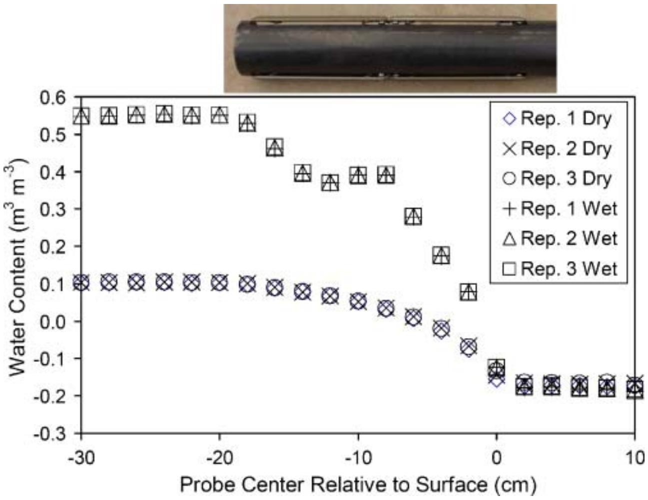

Fig. 3. Axial response of the Trime T3 system in air-dry and saturated soils. A photograph of the probe is scaled to match its length with the *x*-axis scale of the graph. The response in air-dry soil was asymmetrical. The response in saturated soil was also asymmetrical and showed an intermediate peak coincident with the midpoint of the probe where the signal is carried on a flexible conductor between the upper set of plates on the right and the lower set on the left.

Calibrations

Calibration of the EnviroSCAN and Diviner 2000 systems was straightforward, and these systems responded similarly to the three soils (Table 4). Data for Soils A and B plotted together for each system, so a common calibration for the A and B soils was obtained for each system. Data for Soil C did not plot on top of that for Soils A and B, particularly at the wet end, so separate calibrations for Soil C were obtained for each system. The calibration model used was the power function used by Baumhardt et al. (2000), which, like the factory calibration, includes an intercept term. The RMSE of regression, an indicator of calibration accuracy, was between 0.018 and 0.025 m^3 m^{-3} for all calibrations of the EnviroSCAN and Diviner 2000 systems. Positive intercept values ranging from 0.024 to 0.041 m^3 m^{-3} indicated that these calibrations are inaccurate at the extreme dry end, which is understandable since we did not have data for water contents less than the air-dry soil water contents, which ranged from 0.041 to 0.056 m^3 m^{-3}. Calibrations fitted using a power equation without an intercept term, as was done by Paltineanu and Starr (1997), did not fit the data well at either the dry or wet ends. This brings up the question of the nature of water held by these soils at <0.04 or 0.05 m^3 m^{-3}. Water that is not given up during prolonged air drying is closely bound to soil particles and does not respond to electromagnetic waves as does free water. Thus, it is reasonable to use an intercept term in calibration models for these two EM sensors, accepting that bound water is not represented by these calibrations even though it may be driven off by oven drying.

Table 4. Calibration equations for EnviroSCAN, Diviner 2000, PR1/6, and Trime T3 soil water content sensing systems in three soils. All coefficients are significant at the P = 0.01 level.

Soil	Soil water sensor	N	r^2	RMSE
	EnviroSCAN†			
A&B	$\theta_v = 0.024 + 0.605 S_F^{3.812}$	178	0.993	0.022
C	$\theta_v = 0.041 + 0.781 S_F^{4.981}$	90	0.996	0.018
	Diviner 2000			
A&B	$\theta_v = 0.034 + 0.457 S_F^{5.421}$	336	0.992	0.024
C	$\theta_v = 0.028 + 0.563 S_F^{6.182}$	192	0.993	0.025
	Trime T3‡			
A&B	$\theta_v = 0.017 + 5.81\text{E-}8 \times T_P^{2.426}$	310	0.993	0.023
C	$\theta_v = 0.018 + 7.48\text{E-}9 \times T_P^{2.752}$	158	0.997	0.016
	Delta T PR1/6§			
	Data from Days 207 and 212, 2002 omitted:			
A&B	$\theta_v = -0.0003 + 2.11(V)^{2.307}$	480	0.985	0.029
C	$\theta_v = 0.0011 + 2.15(V)^{2.318}$	239	0.986	0.026
	All data included:			
A&B	$\theta_v = 3.36(V - 0.0128TV)^{2.155}$	562	0.981	0.037
C	$\theta_v = 5.38(V - 0.0124TV)^{2.592}$	287	0.970	0.052
A&B	$\theta_v = 2.39(V - 1.47\sigma_a V)^{2.121}$	562	0.956	0.058
C	$\theta_v = -0.613 + 1.10(V - 6.07\sigma_a V)^{0.3252}$	287	0.968	0.054
	Conventional TDR¶			
A, B, C	$\theta_v = -0.182 + 0.1271[c_o t_t/(2L)] - 0.004933[\sigma_a/(2\pi f_{vi}\varepsilon_o)]^{0.5}$	3879	0.997	0.010
	CPN 503DR Neutron Moisture Meter#			
A	$\theta_v = -0.0051 + 0.2331 C_R$	6	0.997	0.004
B	$\theta_v = -0.1054 + 0.2425 C_R$	24	0.988	0.008
C	$\theta_v = -0.0454 + 0.2079 C_R$	20	0.992	0.006

† S_F is scaled frequency.
‡ T_P is pseudo transit time.
§ V is voltage (V); T is temperature (°C), and σ_a is bulk electrical conductivity (S/m).
¶ t_t is travel time (s), and f_{vi} is effective frequency (Hz). Result from Evett et al. (2005).
# C_R is count ratio. The NMM was field calibrated.

Our EnviroSCAN calibrations were similar to that of Baumhardt et al. (2000) for pooled data from the Olton soil sampled 180 km south of Bushland, a sandier soil that is otherwise similar to Pullman (Fig. 4). Our calibrations and that of Baumhardt et al. (2000) exhibit more sensitivity to changes in scaled frequency at water contents >0.2 m^3 m^{-3} and less sensitivity to changes in S_F at water contents <0.1 m^3 m^{-3} than does the factory calibration (Fig. 4). Our calibrations indicate that noise in estimated water contents due to noise in scaled frequency measurements would increase as the soil be-

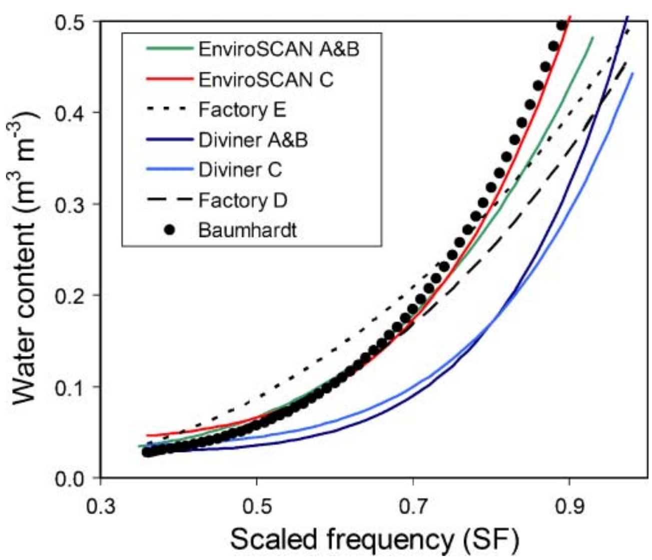

Fig. 4. Calibration curves for the EnviroSCAN system for the combined data from Soils A and B and for Soil C, compared with the factory calibration (Factory E) and the calibration of Baumhardt et al. (2000) in the Olton soil, and calibration curves for the Diviner 2000 system for the combined Soils A and B data and for the C soil, compared with the factory calibration (Factory D).

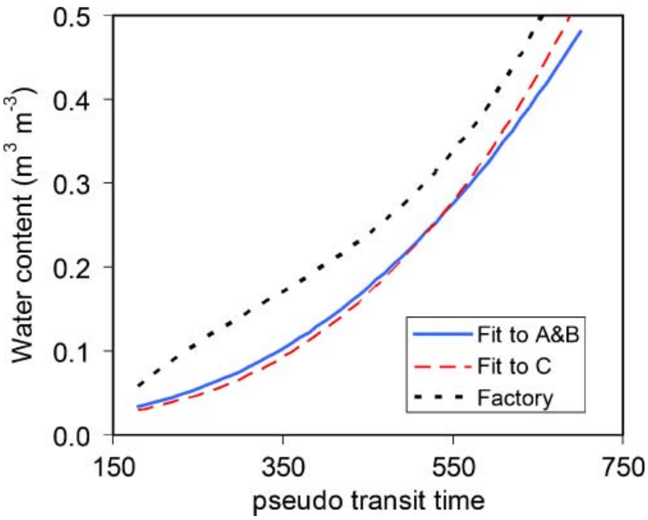

Fig. 5. Calibrations of the Trime T3 tube probe for the combined data from Soils A and B, and for Soil C, compared with the factory calibration.

comes wetter, if noise in S_F measurement is constant across its range.

Calibrations for the Diviner 2000 were similar to those for the EnviroSCAN system in that Soils A and B plotted together, allowing a common calibration for both soils (Table 4, Fig. 4). Again, the calibration for Soil C was different. And again, the Diviner 2000 was more sensitive to changes in water content at smaller water contents and less sensitive at larger water contents. However, in our soils there were greater differences from the factory calibration for the Diviner 2000, except at the air-dry and saturated ends. For all soils, all calibrations for the EnviroSCAN and Diviner 2000 resulted in approximately the same estimates of water content at the dry end. Calibration differences between soils increased as the soil water content increased, indicating a link to soil σ_a, which similarly increases with θ_v and which is small and nearly identical for all three soils at the dry end, but increases to ~1.5 dS m^{-1} at the wet end for Soils A and B, and one-half of that for Soil C. Calibrations for the EnviroSCAN system deviated from the factory calibration most at the wet end. For the Diviner 2000, differences from the factory calibration were largest in the mid range of θ_v. For both sensors, maximum differences from factory calibrations were on the order of 0.1 m^3 m^{-3}.

The Trime T3 system produced similar calibrations in all soils, but again data for Soil C was different enough at the wet end to justify a separate calibration equation (Table 4). For equivalent values of pseudo transit time, our calibrations resulted in smaller estimates of water content across the entire range than did the factory calibration (Fig. 5). The power equation that we used (Table 4) provided a more reasonable fit to the data near the dry end than was shown by the fourth-order polynomial used by the manufacturer. The nonlinearity of our calibrations and that of the manufacturer is another indication that the Trime device does not work like a TDR device. In our soils, calibration of conventional TDR systems is essentially linear with travel time. The Trime device calibration is more similar to the calibrations of capacitance devices presented here, including the differences between calibrations in different soils at the wet end. We believe that this is due to sensitivity of the Trime transit time measurement method to the combined effects of σ_a and T, as we will discuss later in the section on temperature sensitivity. Differences from factory calibration were largest at water contents <0.1 m^3 m^{-3}, with differences being as large as 0.07 m^3 m^{-3}.

Calibration of the Delta-T PR1/6 system was complicated by the large temperature sensitivity of this system in wet soil. When the soil was dry, the PR1/6 output was not very temperature sensitive (Fig. 6), but at the wet end, a temperature increase from ~21°C on Days 56 and 67 of 2002 to ~30°C on Days 207 and 212 of 2002 caused an increase in output of ~0.16 V, equivalent to a bias of 0.026 m^3 m^{-3} °C^{-1} if using the factory calibration for clay soil (Fig. 6, left). At the dry end, a temperature decrease from ~35°C on Days 199 and 201 of 2001 to

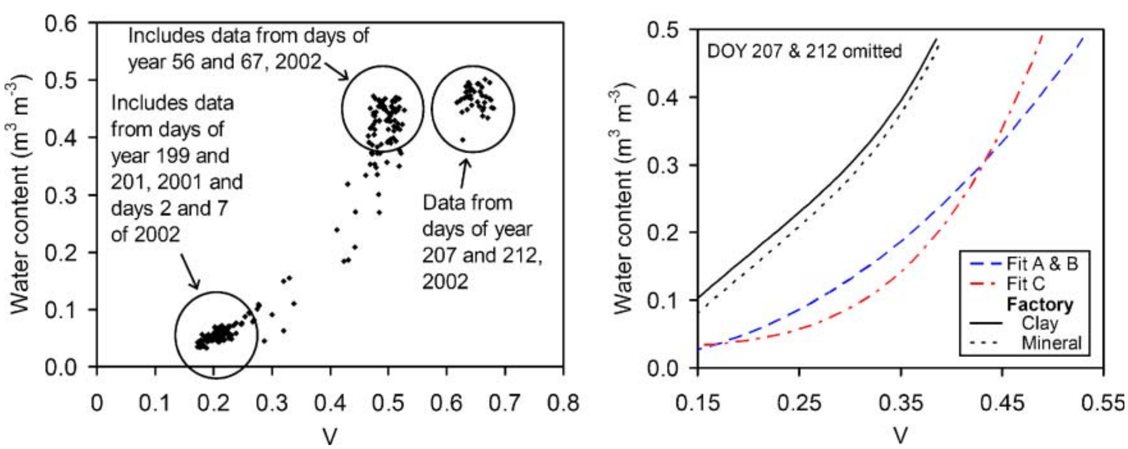

Fig. 6. (Left) Data of water content from the TDR system in soil B versus output (V) from the PR1/6 for Soil B. Data from the wet end are from warm summer days (Days 207 and 212) plot well to the right of those from cool winter days, indicating that output from the PR1/6 is increasing with soil temperature. In contrast, on the dry end data from warm summer days (Days 199 and 201) plots in the same location as those from cold winter days. Except for Days 199, 201, 207, and 212, all data shown were acquired between Days 2 and 67 of 2001. (Right) Calibrations for Soils A and B combined and for Soil C when Days 207 and 212, 2002 are omitted, compared with the factory calibration.

~18°C on Days 2 and 7 of 2002 caused little change in output. Omitting data from Days 207 and 212 of 2002 (and thus ignoring temperature effects), resulted in calibration equations similar to those of the other capacitance sensors in that data for Soils A and B plotted together in plots of water content versus sensor output, and Soil C plotted apart, particularly at the wet end. Also, like the EnviroSCAN, Diviner, and Trime T3 systems, calibrations in our soils were quite different from the factory calibrations (either "clay" or "mineral," Fig. 6, right). But, these differences were much larger for the Delta-T system. For a given value of sensor output, water content in our soils was always smaller than that indicated by factory calibrations.

Several nonlinear regression calibration models including soil temperature as an independent covariable were tried while including the data from Days 207 and 212 of 2002. The best of these resulted in calibrations in terms of sensor output V (V) and T (°C) with coefficients of determination $\geq$0.97 and RMSE values of 0.037 $m^3\ m^{-3}$ for Soils A and B (combined data) and 0.051 $m^3\ m^{-3}$ for Soil C (Table 4, Fig. 7). Since the temperature effect in these soils is largely tied to the increase of soil bulk electrical conductivity (σ_a) with temperature, attempts were made to calibrate in terms of sensor output and σ_a, resulting in similar values of r^2 and RMSE for soil C, but with an unrealistically negative intercept. For the combined Soil A and B data, inclusion of an intercept term resulted in nonsignificant coefficient estimates, but omission of the intercept term resulted in highly significant fitted parameters and a reasonable compound curved surface (Fig. 7). For calibrations including T or σ_a the calibrations were compound curved surfaces similar to those in Fig. 7, with little effect of T or σ_a at small values of θ_v, and increasing effects of T and σ_a as the soils wetted.

A single calibration for conventional TDR estimated water content with accuracy of 0.01 $m^3\ m^{-3}$ in all three soils (Table 4) (Evett et al., 2005). Separate calibrations were required for each soil with the NMM field calibration, but calibration accuracies were better than 0.01 $m^3\ m^{-3}$ (Table 4).

Temperature Effects in Dry and Wet Soils

Temperatures in the soil columns varied diurnally by up to 16°C due to radiational heating and cooling in the green house. Temperature variations decreased with depth, indicating that the reflective shielding was effective in preventing heat loading on the sides of the columns. Corresponding soil column masses indicated that temperature effects on water content derived from mass sensing were $< 0.01\ m^3\ m^{-3}$. Water content determined with each device, using both factory calibrations and the calibrations reported in this paper, was linearly regressed vs. temperature using data from both the air-dry and saturated end points when water content in the columns was invariant over time. Soil type did not influence the relationship between reported water content and soil temperature of the EnviroSCAN system (Fig. 8). Soil-specific calibration decreased the observed temperature dependency at the air-dry end, but increased it to 0.0017 $m^3\ m^{-3}\ °C^{-1}$ at the saturated end (Table 5). The Diviner responded similarly, but the temperature sensitivity at the saturated end was larger (0.0030 $m^3\ m^{-3}\ °C^{-1}$) using the soil-specific calibrations.

For the Delta-T PR1/6, the sensitivity was small in air-dry soil, changing to 0.0251 $m^3\ m^{-3}\ °C^{-1}$ for saturated soil using the factory calibration. When the calibration including temperature as an independent variable was used, the sensitivities were negative and larger in magnitude at the air-dry end and smaller at the saturated end. If the calibration that ignored temperature was used (omitting Days 207 and 212 of 2002), then the sensitivity was 0.0089 $m^3\ m^{-3}\ °C^{-1}$ for saturated soil. Thus, the calibration that included temperature as a covariate overcorrected for temperature sensitivity at the wet end, even though it succeeded in reducing the gross error in estimated water contents caused by a large difference

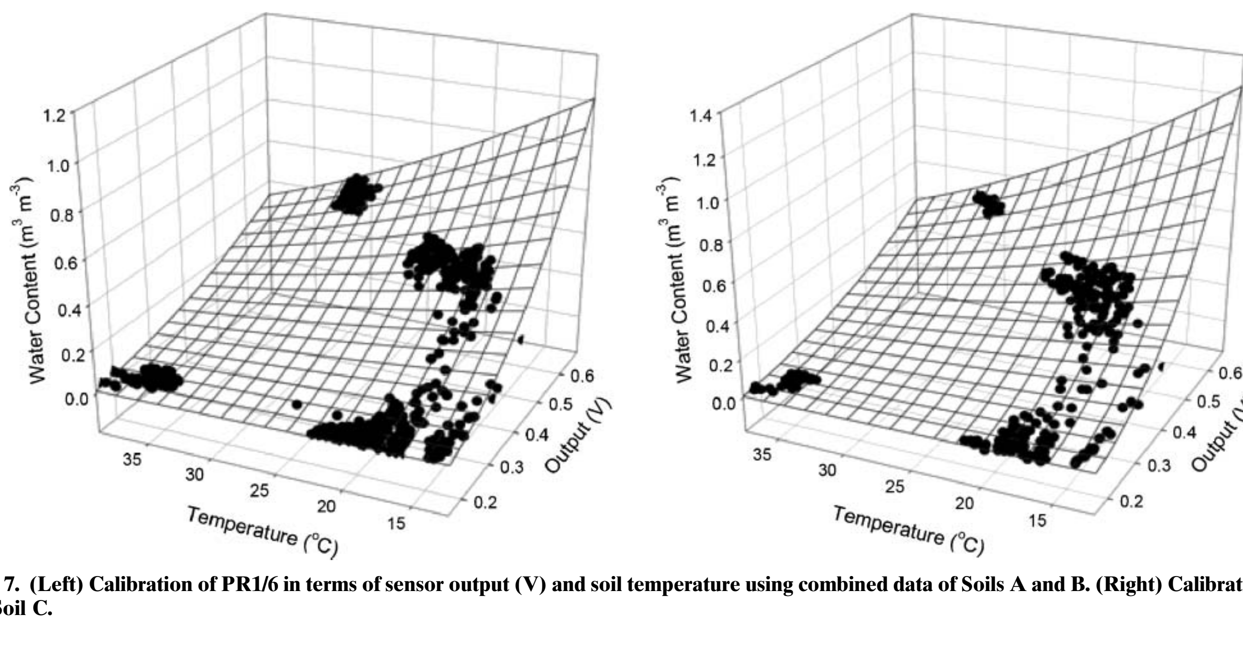

Fig. 7. (Left) Calibration of PR1/6 in terms of sensor output (V) and soil temperature using combined data of Soils A and B. (Right) Calibration for Soil C.

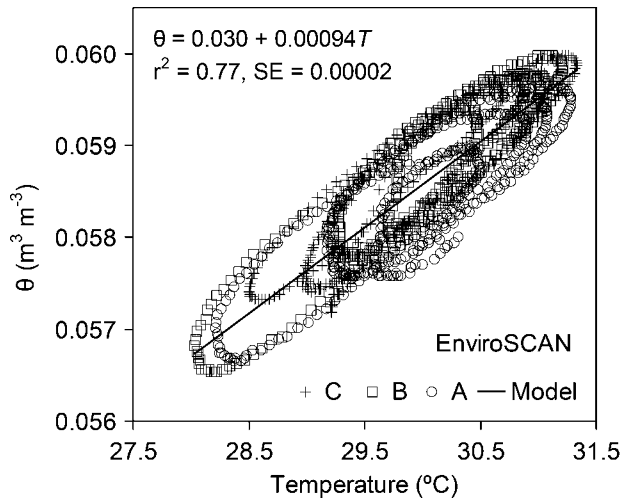

Fig. 8. Example of significant temperature effects on water content values reported by the Sentek EnviroSCAN in three air-dry soils.

in temperature (0.55 $m^3 m^{-3}$ for a 21°C temperature change at the saturated end, or 0.0262 $m^3 m^{-3}$ °C^{-1}).

Soil-specific calibrations reduced the temperature sensitivity of the Trime T3 sensor to 0.0047 $m^3 m^{-3}$ °C^{-1} for air-dry soil, increasing to 0.0146 $m^3 m^{-3}$ °C^{-1} for saturated soil. These results are not in agreement with the data from the calibration, for which the data from Days 56, 67, 207, and 212 of 2002 plotted together, indicating little effect of temperature. This suggests that the temperature sensitivity observed for the Trime system is related not to soil temperature changes but to air temperature changes, which would affect the coaxial cable and Trime FM measurement unit. Data for the calibrations were taken at approximately the same time of day every time, reducing the daily but not the seasonal temperature variation observed during calibration. Data for the temperature dependency studies were taken on 30-min intervals for periods 24 h or longer, during which air temperature in the greenhouse changed greatly. We conjectured that the temperature sensitivity observed with the Trime system was related to either the cable or to the Trime FM unit that generates the fast rise time pulses and times the return of those pulses. Evett (2000b) measured changes in TDR pulse transit times as large as 0.28 ns in coaxial cables over 24-h periods, and these were strongly related to ambient temperature variations of as much as 17°C. A 0.28-ns variation in t_t for this temperature range would result in an approximately 0.0015 $m^3 m^{-3}$ °C^{-1} variation in estimated water content using Eq. [2], too small to account for all of the temperature-related variations in Trime-estimated water contents observed here. Thus, we expect that the major influence of temperature is on the Trime FM unit's determination of transit time, either due to temperature instability of the electronic circuits or due to inadequacy of the transit time determination method to fully account for effects of σ_a.

Data from Laurent (personal communication, 2003) illustrate an explanation related to soil temperature and the transit time determination method used in the Trime-FM unit (Fig. 9). In a uniform smectitic clay soil profile, neutron probe data indicated uniform water contents with depth, but readings from the Trime system in the same polycarbonate access tube indicated different water contents. Waveforms, acquired with a Tektronix 1502C TDR cable tester connected to the Trime coaxial cable at the point of connection with the Trime-FM measuring unit and subjected to conventional TDR travel time analysis, also showed equal water contents. However, transit times that would be measured using a voltage comparator are different for the different waveforms (Fig. 9). This is because the slope of the reflected TDR pulse decreases with depth in this profile, probably due to warmer temperatures at depth and the large amount of smectite clay in this soil, which would lead to appreciable σ_a even in a nonsaline soil. To control this effect, the Trime system uses an algorithm that reduces the comparative voltage at which transit time is determined as the value of σ_a increases and the reflected waveform height decreases. Apparently, this algorithm is not completely effective in some soils, including those at Nancy, France and in the Texas High Plains. Further study is needed to determine the exact causes of temperature sensitivity with the Trime system.

Table 5. Temperature effects on water content values estimated using the factory calibrations and the soil-specific calibrations (New) reported herein from data measured in air-dry and in saturated soil. The TDR system used the calibration of Evett et al. (2005) or Topp et al. (1980). Slopes were significant at the P = 0.001 level†.

Instrument, calibration	Air-dry soil			Saturated soil		
	Slope	r^2	SE	Slope	r^2	SE‡
	($m^3 m^{-3}$) °C^{-1}		($m^3 m^{-3}$) °C^{-1}	($m^3 m^{-3}$) °C^{-1}		($m^3 m^{-3}$) °C^{-1}
Delta_T PR1/6, factory	0.0009	0.76	0.00003	0.0251	0.94	0.00024
Delta-T PR1/6, new§	0.0005	0.76	0.00001	0.0089	0.94	0.00009
Delta-T PR1/6, new¶	−0.0015	0.98	0.00001	−0.0173	0.99	0.00007
Diviner, factory	0.0005	0.65	0.00005	0.0019	0.77	0.00010
Diviner, new	0.0005	0.65	0.00005	0.0030	0.77	0.00016
EnviroSCAN, factory	0.0009	0.77	0.00002	0.0010	0.88	0.00001
EnviroSCAN, new	0.0005	0.74	0.00001	0.0017	0.87	0.00002
Trime T3, factory	0.0092	0.52	0.00115	0.0204	0.75	0.00117
Trime T3, new	0.0047	0.52	0.00059	0.0146	0.75	0.00084
TDR (Topp et al., 1980)	0.0005	0.33	0.00005	0.0024	0.61	0.00006
TDR (Evett et al., 2005)	0.0006	0.32	0.00006	0.0005	0.02	0.00011

† Regressions and regression slopes were not significant for the TDR and neutron probe devices.
‡ SE is the standard error of the slope.
§ For calibration excluding Days 207 and 212 and with no temperature variable.
¶ For calibration including Days 207 and 212 and a temperature variable.

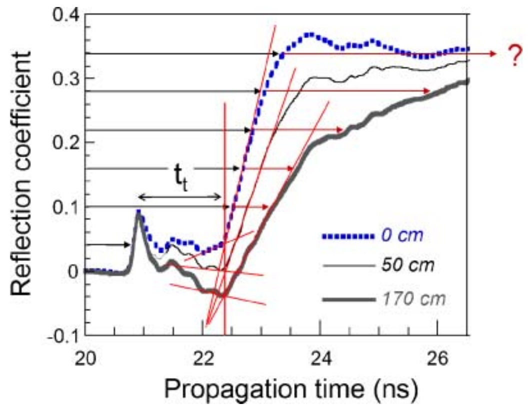

Fig. 9. Waveforms collected from a Trime T3 probe using a Tektronix 1502 C TDR cable tester connected to the coaxial cable at the Trime-FM measuring device. At each depth shown, a waveform was collected with the top end of the probe waveguides placed at that depth in an access tube placed in a uniform smectitic clay soil. Water content as measured with a neutron probe was uniform throughout the profile. Travel time analysis by intersection of tangent lines (red with a vertical red line indicating the intersections) showed that travel time was practically equal at all depths, indicating that conventional TDR would predict equal water contents throughout the profile, although the Trime-FM did not. The relative lengths of horizontal arrows drawn from the left *y* axis to the waveforms indicate the changes in transit time for different set-point voltages at which a comparator circuit would time the arrival of the reflected pulse. The transit times illustrated in this manner are greater for the waveforms from deeper within the profile even though water contents are the same. The differences in slope of the reflected pulse are due to differences in soil temperature and/or bulk electrical conductivity. Data courtesy of Jean-Paul Laurent, Chargé de Recherches au CNRS, Laboratoire d'étude des Transferts en Hydrologie et Environnement, Grenoble, France.

Temperature sensitivities for conventional TDR were determined using both the Topp et al. (1980) calibration and the calibration in terms of travel time, bulk electrical conductivity, and effective frequency of Evett et al. (2005). Sensitivities were computed both for single sensors at the 25-cm depth (as for all the other sensors studied) and for the column mean water content as determined by the eight TDR probes in each column. Sensitivities for single probes were not significant (Evett et al., 2005). When column mean water contents were used, noise in individual readings was canceled out by the averaging process, resulting in statistically significant sensitivities. In air-dry soils, temperature sensitivity was small using both calibrations. The r^2 values were smaller ($\leq$0.33) for TDR than for any other sensor, indicating the weak linear relationship (Table 5). For saturated soils, temperature sensitivity using the Topp et al. (1980) calibration was larger (0.0024 m^3 m^{-3} °C^{-1}) than sensitivities of the EnviroSCAN and Diviner 2000 using factory calibrations. Using the calibration of Evett et al. (2005) in saturated soils, the temperature sensitivity was smaller (0.0005 m^3 m^{-3} °C^{-1}) than that for any other EM device, and the linear relationship was nearly nonexistent (r^2 = 0.02).

Precision in Dry and Wet Soils

Precision was assessed both as a running mean SD of a fixed number of water content determinations and as the SD of all determinations taken during increasingly long periods of time. The latter value of SD would include any increase in variability due to temperature changes over each period. Compared with results from the other sensors, for the relatively temperature insensitive NMM and TDR the value of SD was relatively stable with increasing sampling time and with time, being at most ~0.001 m^3 m^{-3} for the NMM and ~0.002 m^3 m^{-3} for TDR in air-dry soils, and ~0.003 and ~0.007 m^3 m^{-3} for NMM and TDR, respectively, in saturated soils (Table 6). For TDR in saturated soils, SD

Table 6. Standard deviations (m^3 m^{-3}) for six soil water sensing systems calculated as the mean of SD values calculated over short intervals (SD of four values for 1 to 2 h) over periods of 1 to 4 d, and taken as the long-term value of SD calculated using data from the entire period (1–4 d). Values were calculated using both the factory and the soil-specific calibrations determined in the present study. Missing values indicate that data were not available on 0.25- to 0.5-h intervals for periods exceeding 0.8 d.

			Air-dry soils			Saturated soils		
Sensor		Calibration	A	B	C	A	B	C
Delta-T PR1/6	mean	factory		0.000 12			0.0023 06	
		soil specific		0.000 06			0.0011 56	
	long-term	factory		0.002 42			0.0838 05	
		soil specific		0.001 16			0.0536 77	
Diviner	mean	factory	0.000 21			0.000 45		
		soil specific	0.000 18			0.000 73		
	long-term	factory	0.000 52			0.002 13		
		soil specific	0.000 43			0.003 45		
EnviroSCAN	mean	factory	0.000 06	0.000 06	0.000 07	0.000 10	0.000 08	0.000 07
		soil specific	0.000 03	0.000 04	0.000 03	0.000 12	0.000 12	0.000 14
	long-term	factory	0.000 75	0.000 79	0.000 92	0.001 52	0.001 18	0.001 26
		soil specific	0.000 46	0.000 52	0.000 35	0.002 07	0.001 80	0.002 65
NMM	mean	factory	0.000 58				0.001 61	
		soil specific	0.000 91				0.002 40	
	long-term	factory	0.001 16				0.002 33	
		soil specific	0.001 67				0.003 46	
TDR	mean	factory	0.000 50	0.000 65	0.000 99	0.001 81	0.001 84	0.000 69
		soil specific	0.000 56	0.000 72	0.001 10	0.004 02	0.004 71	0.001 05
	long-term	factory	0.000 97	0.001 32	0.001 78	0.004 65	0.004 76	0.001 34
		soil specific	0.001 05	0.001 44	0.001 95	0.006 33	0.007 15	0.001 77
Trime T3	mean	factory	0.001 38				0.002 97	
		soil specific	0.000 69				0.002 12	
	long-term	factory	0.009 02				0.018 32	
		soil specific	0.004 60				0.013 14	

was two to four times as large in Soils A and B as in Soil C due to the increased noise in determination of travel time caused by the larger bulk electrical conductivity in Soils A and B (reduced slope of the second rising limb of the waveform; see Evett, 2000b).

Values of SD for the Delta-T PR1/6, Diviner 2000, EnviroSCAN, and Trime T3 systems fluctuated with time and increased with increasing time during which water content values were included in the calculation (e.g., Fig. 10). Fluctuating and increasing SD values were due to the temperature sensitivity of these instruments and reached a maximum value within one-half day for all but the Delta-T PR1/6. For the latter instrument, SD values continued to increase to as large as 0.084 m^3 m^{-3} with increasing numbers of data used in the calculation past 3 d of data, although a local maximum was reached in one-half day. For the less temperature-sensitive EnviroSCAN and Diviner 2000 instruments, short-term (four-value means in Table 6) SD values were <0.001 m^3 m^{-3}, while short-term SD values in saturated soils were as large as 0.0030 m^3 m^{-3} for the Trime T3, and as large as 0.0023 m^3 m^{-3} for the Delta-T PR1/6.

Except for TDR, in air-dry soils the soil-specific calibrations reported herein caused SD values to decrease by approximately 50% because slopes of soil-specific calibrations tended to be smaller on the air-dry end than

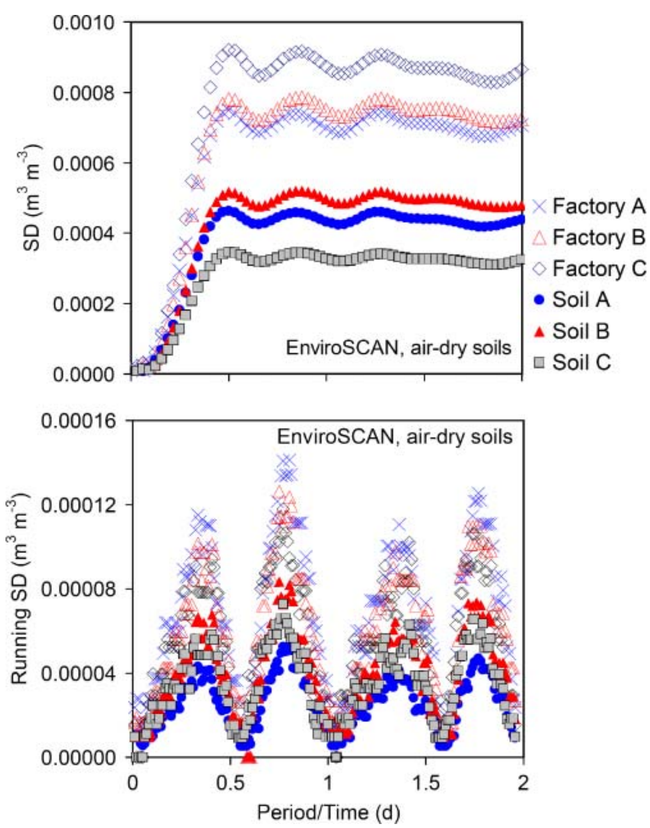

Fig. 10. Example of variation over time of standard deviation (SD) values for the EnviroSCAN system. Data are for air-dry soils. The SD (top) is calculated using all data values beginning with zero time and continuing until the time at which the data are plotted. The Running SD is the SD for four consecutively acquired values beginning at each time (bottom) at which the data are plotted; it shows a periodic temperature effect.

slopes of factory calibrations. For TDR, in both air-dry and saturated soils, SD values increased when soil-specific calibration was used because the soil-specific calibration involved determining both the bulk electrical conductivity and the effective frequency in addition to the travel time (Evett et al., 2005), which added some random noise to the resulting water content values. In saturated soils, the effect of soil-specific calibrations was mixed, resulting in some decrease in SD for the Delta-T PR1/6 and Trime T3 instruments, but resulting in increased SD values for the EnvironSCAN and Diviner 2000 instruments due to the larger slopes of the calibration curves for the latter instruments as compared with factory curves at the saturated end.

In both air-dry and saturated soils, values of SD were soil specific, but not in any particular ranking order. Values of SD were larger (from ~2 to 40 times) in saturated soils than in air-dry soils, regardless of the instrument, soil type, or calibration used.

DISCUSSION AND CONCLUSIONS

Using the factory calibrations, the conventional TDR system was more accurate than the other EM systems, all of which misestimated water content more on both the air-dry and saturated ends than did TDR. The EnviroSCAN, Diviner 2000, NMM, and Trime T3 systems exhibited roughly equivalent accuracies, and the Delta-T PR1/6 was not accurate. With the exception of conventional TDR, all of the devices required soil-specific calibrations to achieve accuracies better than ± 0.04 m^3 m^{-3}. Using factory calibrations, all of the EM systems were more accurate at the air-dry end than at the saturated end, probably due to the increase in bulk electrical conductivity as these soils saturated. Of the capacitance sensors, the accuracy at the saturated end, where effects of σ_a and T were largest, was best for the sensor with the largest measurement frequency (Diviner 2000) and worst for the sensor with the smallest measurement frequency (Delta-T PR1/6), emphasizing the importance of greater measurement frequencies in capacitance sensors. Kelleners et al. (2005) suggested that capacitance sensor measurement frequencies should be >500 MHz—all of the capacitance sensors studied here operate at frequencies less than this criterion. Soil-specific calibrations produced accuracies (RMSE values) on the order of 0.02 m^3 m^{-3} for the EnviroSCAN, Diviner 2000, and Trime T3 systems. For the first two, RMSE values were slightly better than those achieved by Baumhardt et al. (2000), but not as good as the 0.009 m^3 m^{-3} value achieved by Paltineanu and Starr (1997). Soil-specific calibration accuracy for the PR1/6 was on the order of 0.04 to 0.05 m^3 m^{-3}. Calibrated accuracies for the TDR and NMM were twice as good as those for EM systems employed in access tubes.

The conventional TDR system was insensitive to soil temperature fluctuations when measurements at a single depth with a single sensor were correlated with temperature at that depth, that is, the procedure that was followed for all other sensors in this study. However, in a companion study (Evett et al., 2005), a temperature dependency was found when the mean of water contents from several probes was considered. We think the apparent lack of temperature sensitivity found when using one sensor is due to random error (noise) in travel time determination, and that this noise was canceled out when averaging data from several probes, thus allowing the underlying temperature sensitivity to become clear in the companion study. This, and the relatively small temperature dependency of conventional TDR in many soils, may explain why some studies have reported no temperature sensitivity for TDR. Temperature sensitivity of TDR was nearly eliminated by including bulk electrical conductivity and effective frequency in a single calibration for these three soils.

The EnviroSCAN and Diviner 2000 were moderately sensitive to temperature at the saturated end, probably due to sensitivity to bulk electrical conductivity, which varies with temperature. Both the Delta-T and Trime were quite sensitive to temperature fluctuations, probably due to the relatively small measurement frequency of the former and to temperature-sensitive transit time measurement algorithms in the latter. The PR1/6 was most sensitive to soil temperature changes. Although the Delta-T and Trime systems can be calibrated in the laboratory for a specific soil, their temperature sensitivity leads to the conclusion that they cannot be recommended for field work in soil profile water content determination where daily or seasonal variations in temperature could cause large errors in water content determination.

Precision was affected by soil type, temperature fluctuations, the soil wetness, and the calibration equation used. Precision of all instruments was worse in saturated soils than in air-dry soils, with values of SD as large as 0.02 and 0.08 $m^3\ m^{-3}$ for the Trime T3 and Delta-T PR1/6, respectively. Precision determined by repeated measurements in short time periods gives false confidence, as precision determined from longer periods was larger for all instruments studied, due to temperature interferences. However, the increase of SD with longer periods of measurement was minimal for the NMM and TDR instruments because of their relative lack of temperature sensitivity.

The small measurement volumes of the Delta-T, Diviner, and EnviroSCAN probes will make them sensitive to small-scale variations in soil water content and bulk density close to the access tube, and sensitive to any soil disturbance during access tube installation. For Soils A and B, our calibration equations tended to be more curvilinear than the factory calibrations, with steeper slopes at the wet end. This means that variations in the output of the sensors (whether that be a voltage, a frequency, or a pseudo transit time) near the wet end will cause greater variations in estimated water content using our soil-specific calibrations than using factory calibrations. The curvilinear nature of these calibration equations also means that variability in the output signal will cause variability of estimated field water contents to increase as the soil wets. This might be expected to interact with the fact that the measurement volumes of the capacitance sensors (EnviroSCAN, Diviner, and PR1/6) decrease as soil water content increases, possibly causing an increase in apparent variability of water content sensed in wetter field soils. The small measurement volumes also mean that field calibrations may not succeed in many soils because the volume of soil sensed by these probes is too small to allow sampling within that volume with existing volumetric soil sampling equipment.

The NMM was insensitive to soil temperature and had the largest axial response height in dry soil, though slightly smaller than that of the Trime probe in saturated soil. While the axial response height of the Trime probe is relatively large, its radial response is unknown, but expected to be smaller than that of the NMM. Field tests will determine its sensitivity to variations in field soil water content. The measurement volume of the NMM is known to be roughly spherical. Because of the larger measurement volume of the NMM, it should be less sensitive to small-scale variations in soil properties and to soil disturbance caused during access tube installation. For these reasons, and because we know that the NMM can be accurately field calibrated (Hignett and Evett, 2002), it remains the recommended probe for profile soil water content determination from within access tubes. Of the EM sensors used in access tubes, only the EnviroSCAN and Diviner appear to be temperature insensitive enough to be useful for field work, but their small measurement volumes indicate problems with variability of readings in field settings. Three field studies of spatial sensitivity supporting this have been concluded and will be reported in future.

Needed improvements in EM soil water content sensors include reduced temperature sensitivity, increased measurement volume, decreased sensitivity to soil type and bulk electrical conductivity, and more linear calibrations. Our results with the Delta-T PR1/6 sensor indicate that sensing of soil temperature and/or bulk electrical conductivity as covariates may be insufficient to fully correct water content estimates from some EM sensors. Application of an electric circuit model to correct EnviroSCAN calibrations in a saline silty clay was also only partially successful for Kelleners et al. (2004a). Increasing the measurement frequency of the capacitance sensors should lessen the influence of bulk electrical conductivity and temperature, but perhaps at the expense of decreasing already small measurement volumes.

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